9.7 GRAVITY WAVES

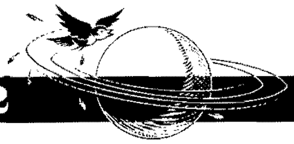
gravitational energy moving at light speed

Gravity waves from collapsing matter

In the depths of an ill-fated, collapsing star, billions upon billions of tons of mass cave in and crash together. The crashing mass generates a wave in the geometry of space — a wave that rolls across a hundred thousand light-years of space to "jiggle" the distance between two mirrors in our Earthbound gravity-wave laboratory.

A cork floating all alone on the Pacific Ocean may not reveal the passage of a wave. But when a second cork is floating near it, then the passing of the wave is revealed by the fluctuating separation between the two corks. So too for the separation of the two mirrors. There is, however, this great difference. The cork-to-cork distance reveals a momentary change in the two-dimensional geometry of the surface of the ocean. The

BOX 9-2



COMPACT STELLAR OBJECTS

Three kinds of astronomical objects exist comparable in mass to Sun but very much smaller. Two of these have been observed; the third seems an inevitable result of Einstein's theory.

A **white dwarf star** is a star of about one solar mass, with radius about 5000 kilometers. (The radius of Earth is 6371 kilometers.) This gives the white dwarf a density of approximately 10^9 kilograms/meter^3 (or one metric ton per cubic centimeter). As of 1990, approximately 1500 white dwarfs have been identified.

White dwarfs were observed and studied astronomically long before they were understood theoretically. Today we have come to recognize that a white dwarf is a star that quietly used up its fuel and settled gently into this compact state. The electrons and nuclei that make up the body of a white dwarf are not separated into atoms. Instead, the electrons form a gas in which the nuclei swim. The pressure of this "cold" electron gas keeps the white dwarf from collapsing further.

S. Chandrasekhar calculated in 1930 that no white dwarf can be more massive than approximately 1.4 solar masses ("Chandrasekhar limit") without collapsing under its own gravitational attraction. His analysis assumed the mix of electrons and nuclei to be unaltered under compression by a load so heavy, an assumption that had to be modified in later years. Today we recognize that enormous compressions squeeze electrons into combining with protons to make neutrons. At compressions near the Chandrasekhar limit, the electron gas transforms into a neutron gas, the interior of the star becomes a giant nucleus, and the whole nature of the compact object changes to that of a neutron star.

A **neutron star** has roughly the same density as an atomic nucleus, of the order of 10^{17} kilograms/meter^3, or one Earth mass per cube of edge length 400 meters. The radius of a neutron star is approximately 10 kilometers.

mirror-to-mirror distance reveals a momentary change in the three-dimensional geometry of space itself.

How to detect gravity waves

The idea of extracting energy from ocean waves is old. After all, the ability of a water wave to change a distance lets itself be translated into the ability to do work. The same reasoning applies to a gravity wave. Because it can change distance, it can do work. It carries energy. Energy once resident as mass in the interior of a star has radiated out to us and to all the universe.

Of all the workings of the grip of gravity, none is more fascinating or opens up for exploration a wider realm of ideas than a gravity wave. None pushes to a higher pitch the art of detecting a small effect, and none gives more promise of providing an unsurpassable window on cataclysmic events deep inside troubled stars. Nevertheless, no other great prediction of Einstein's geometric theory of gravity stands today so far from triumphant exploitation. As of this writing, not one of the nine ingenious

How often is a neutron star formed? Towards answering this still open question we have one important lead: In our own galaxy we see one supernova explosion on average about every 300 years [most recent supernova in the Large Magellanic Cloud, a satellite structure near our galaxy, on February 23, 1987; one seen by Kepler, October 13, 1604; one seen by Tycho Brahe, November 6, 1572; earlier ones: 1181 A.D.; July 4, 1054 A.D.; 1006 A.D. (the brightest); 185 A.D.; and two possibles in 386 A.D. and 393 A.D.]. In such an event a star teetering on the edge of instability finally collapses. The Niagara Falls of infalling mass in some cases go too far and overcompress the inner region of the star. That region thereupon acts like a spring, or explosive charge, and drives off the outer portions of the star. This explains the spectacular luminosity that is such a prominent feature of a supernova. The core that remains becomes a neutron star in some events, it is believed, in others a black hole.

Neutron stars were predicted in 1934 but not observed until 1968. Many neutron stars spin rapidly — with a period as short as a few milliseconds. A neutron star typically has an immense magnetic field. When that field is aligned at an angle relative to the axis of spin of the star (as in Earth, for example), it sweeps around like a giant whisk brush through the plasma in the space around the star. The periodic shock to the electrons of the plasma from the periodic arrival of this field excites those electrons to radiate periodic pulses of radio waves and visible light — both observed on Earth. Because of this behavior, such neutron stars are called **pulsars**. As of 1990, nearly 500 pulsars have been identified.

A **black hole** is an object created when a star collapses to a size so small that strong spacetime curvature prevents it from communicating outward with the external universe. Even light cannot escape from a black hole, whence its name. No one who accepts general relativity has found any way to escape the prediction that black holes must exist in our galaxy. Strong evidence for the existence of black holes has been found, but it is not yet convincing to all astrophysicists. A black hole can have a mass as small as a few times the mass of our Sun. A black hole of three solar masses would have a "radius" of about 9 kilometers. There is no theoretical upper limit to its mass.

detectors built to this day has proved sensitive enough to secure any generally agreed detection of an arriving gravity wave.

Does any truly simple line of reasoning assure us that gravity will inescapably carry energy away from two masses that undergo rapid change in relative position? Yes is the conclusion of a little story that savors of mythology. The Atlas of our day, zooming through space in free float, insists as much as ever on maintaining physical fitness. He pumps iron, not by raising iron against the pull of Earth's gravity, but by throwing apart two identical great iron spheres, Alpha and Beta. He floats between those minor moons and plays catch with them. Each time they fall together under the influence of their mutual gravity, he catches them, absorbs their energy of infall in his springlike muscles, and flings them apart so that they always travel the same distance before returning. It's an enchanting game, but Atlas finds that it's a losing game. When the masses fly back together, they never yield up to him as much energy as he must supply to throw them apart again. Why not?

Gravity waves result from time delay

Say the central point in two words: time delay. Like any force that makes itself felt through the emptiness of space, the force of gravity cannot propagate faster than the speed of light. This limitation imposes a delay on the attraction between the two iron spheres. Alpha, on each little stretch of its outbound path, feels a pull that originated from Beta when the two were a tiny bit *closer* than they are now. The actual force that's slowing Alpha is therefore a tiny bit bigger than we would judge from thinking of them as stationary at their momentary separation. On its return trip inbound along the same little stretch of path, Alpha experiences a helping pull that originated from Beta when the two had a separation slightly *greater* than its present value. The actual force that's speeding Alpha inward is therefore a tiny bit less than we would judge from thinking of them as stationary at their momentary separation. In each stretch of their outbound trip, the two masses have to do more work against the pull of gravity than they get back — in the form of work done on them by gravity — on the same stretch of path inbound. A calculable amount of energy disappears from the local scene on each out-in cycle of Atlas's exercise. Yet the total energy must somehow be conserved. Therefore the very gravity that steals energy from Atlas and his iron, or from any two

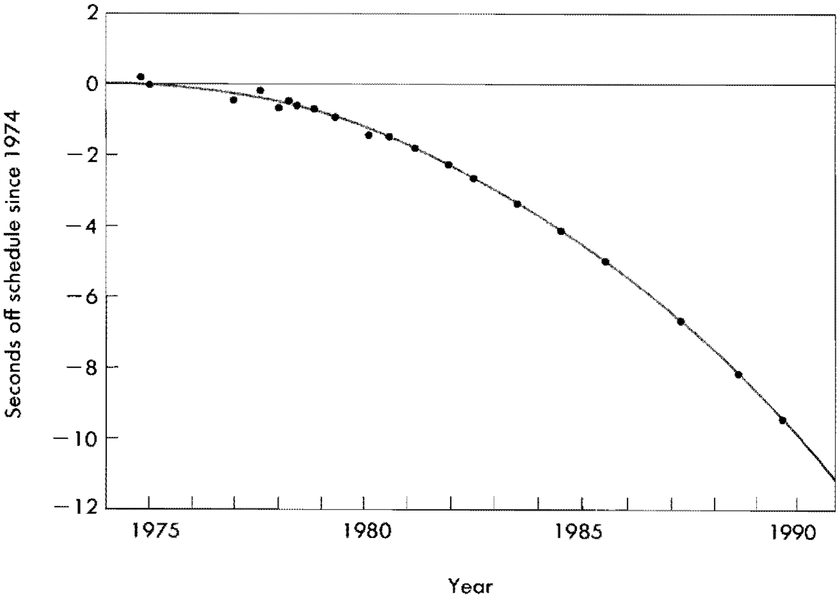


FIGURE 9-7. *Two whirling neutron stars furnish a giant clock, whose time-keeping hand is the line, ever-turning, that separates the centers of those two stars. That hand does not today keep the "slow" schedule (straight horizontal line) one might have expected from its timing as measured in 1974. The downward sloping curve shows gravity-wave theory's prediction of the shortening in the time required to accumulate any specified number of revolutions. The dots show the actual observed shortening in that time.*

masses that rapidly change their relative position, must somehow all the time be transporting the stolen energy to the far-away. That inescapable theft of energy is in its quality, its directional distribution, and its magnitude none other than what Einstein had treated long before under the head of *gravity radiation* and what we now call gravity waves.

Atlas couldn't "see" those gravity waves. Neither have we today yet succeeded in detecting directly the gravity waves we feel sure must be radiating from sources dotted here and there in the galaxy and in the universe. However, we have an exciting indirect confirmation that gravity waves exist — not through their action on any receptor, but through the energy they carry away from a whirling pair of neutron stars. That particular "binary pulsar" first revealed itself to Joseph H. Taylor, Jr., and Russell A. Hulse by periodic pulses of radio waves picked up on the huge disklike antenna at Arecibo in Puerto Rico. As one of these neutron stars spins on its axis, its magnetic field spins with it, giving timing comparable in accuracy to the best atomic clock ever built (Box 9-2). Thanks to this happy circumstance, Taylor and his colleagues have been able to follow the ever-shortening separation of the two stars and the ever-higher speed they attain as they slowly spiral in toward an ultimate catastrophe some 400 million years from now. The timing of the orbits gives us a measure of energy lost as the stars spiral in. No reasonable way has ever been found to account for the thus observed loss of energy except gravitational radiation. As of September 1989, 14 years after first observation, this loss of energy agrees with the rate predicted by theory to better than one percent (Figure 9-7).

Gravity waves steal energy from orbiting neutron stars

Gravity waves and pulses of gravity radiation are sweeping over us all the time from sources of many kinds out in space. Detecting them, however, we are no better than the primitive jungle dweller unable to detect and even totally unaware of the radio waves that carry past her every minute of the day music, words, and messages. However, experimentalists are working out ingenious technology and building detector instrumentation of ever-growing sensitivity (Figures 9-8 and 9-9). Few among them have any doubt of their ability to detect pulses of gravity radiation from one or another star catastrophe by sometime in the first decade of the twenty-first century.

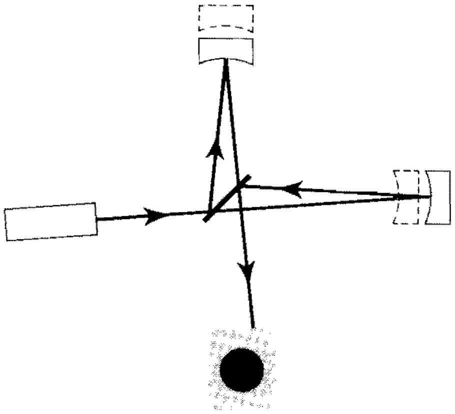


FIGURE 9-8. *The proposed MIT–Caltech gravity-wave detector will (1) use the beam from a laser (left), (2) split it by a device (center) analogous to a half-silvered mirror, (3) send one half-strength beam to one faraway mirror (top) and the other to the other faraway mirror (right), (5) allow these beams to undergo many many reflections (not shown), and (6) recombine them at the detector (bottom). A gravity-wave incident on Earth will slightly shorten the 4-kilometer distance to the one mirror and slightly lengthen the 4-kilometer distance to the other mirror. This relative alteration in the path length of the laser beams, if big enough, amplified enough, and picked up by detectors sensitive enough, will reveal the passage of the gravity wave.*

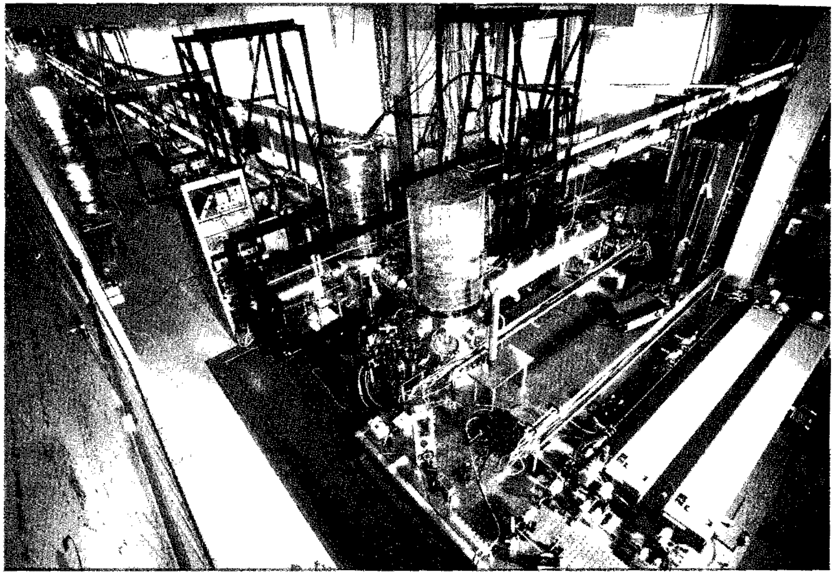


FIGURE 9-9. ***Prototype gravity-wave detector, California Institute of Technology, Pasadena.*** *The laser beam is tailored (lower right) for entry into the beam splitter (located where the two long light pipes meet, just to the left of center in the photograph). The mirrors at the ends of these two evacuated light pipes lie outside the boundary of the photograph.*

Astronomy uses signals of many kinds — light, radio waves, and X-rays among them — to reveal the secrets of the stars. Of all signals from a star, none comes out from deeper in the interior than a gravity wave. Among all violent events to be probed deeply by a gravity wave, none is more fascinating than the dance of death of two compact stars as they whirl around each other and undergo total collapse into . . . a black hole!

[illegible] BLACK HOLE